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Crop yield and weed growth under conservation agriculture in semi-arid Zimbabwe

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ABSTRACT

Constraints to effective weed management may be the main reason for the small area under minimum tillage (MT) in smallholder farming in southern Africa. The effect of maize residue mulching and intensity of hand hoe weeding on the growth of weeds, cowpea (*Vigna unguiculata cv.* IT 86D-719) and sorghum (*Sorghum bicolor cv.* Macia) was investigated in the fifth and sixth years of a conservation agriculture (CA) field experiment at Matopos Research Station (28°30.92′E, 20°23.32′S). The experiment was a split-plot randomized complete block design with three replications. Tillage was the main plot factor (conventional tillage – mouldboard plough compared against MT systems – ripper tine and planting basins) and maize residue mulch rate (0, 4 and 8 t ha^{-1}) the sub-plot factor. Hoe weeding was done either four times (high weeding intensity) or twice (low weeding intensity) during the cropping season. Planting and weeding were done at the same time in all treatments. There was markedly greater early season weed growth in MT systems relative to mouldboard plough (MBP) in both crop species. In sorghum, MT (planting basins: 40.3 kg ha^{-1}; ripper tine: 34.8 kg ha^{-1}) systems had higher cumulative weed biomass measured after planting than MBP (29.9 kg ha^{-1}) system. Maize mulching was generally associated with increased mid- to late-season weed growth in the two crops probably due to improved soil moisture conservation during periods of low precipitation. Weed suppression by the maize mulch was observed only in sorghum and limited to early in the cropping season with no effect observed for the remainder of the sorghum rotation phase. The high weeding intensity treatment had lower weed growth in both crops and better sorghum yield than low weeding intensity. The MT systems had poor crop establishment which translated into low yields. Cowpea grain yield obtained from MT systems was less than 300 kg ha^{-1} compared to 413 kg ha^{-1} in MBP. The poor sorghum establishment in MT systems translated into low grain yield as sorghum grain yield was lowest in planting basins (2602 kg ha^{-1}) and highest in MBP with 4159 kg ha^{-1}. Results suggest that CA systems require early and frequent hoe weeding even after four years to reduce weed infestations and improve crop growth. This higher demand on a smallholder household's limited labor supply throughout the cropping season will be a key determinant of the spread and adoption of CA in southern Africa.

1. Introduction

Conservation agriculture (CA) is being promoted to smallholder farmers in sub-Saharan Africa to increase productivity, reduce farmers' vulnerability to drought, and address low draught power ownership levels and to combat increasing levels of land degradation (http://www.fao.org/ag/ca). In southern Africa, the CA package being promoted comprises the simultaneous application of continuous minimum tillage, a target of at least 30% permanent soil cover and a diversified cropping system of three or more crops in rotation including a legume with concomitant timely field management (Baudron et al., 2007; Twomlow et al., 2008). Although the majority of smallholder farmers in the region are at most practicing some aspects of improved minimum tillage only, yield increases of between 30 and 120% have been reported on farmers' fields in Zambia (Haggblade and Tembo, 2003) and Zimbabwe (Mazvimavi and Twomlow, 2009). The increase in yield is attributed mainly to better crop management through early planting; fertilizer application and improved timeliness of field operations, particularly weed management.

Despite the yield benefits associated with the minimum tillage packages such as planting basins and ripper tine that are being actively promoted throughout sub-Saharan Africa (Twomlow et al.,

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2008); the majority of smallholder farmers' fields are still under conventional plough tillage. The area under minimum tillage rarely exceeds 1 ha per farming household (Baudron et al., 2007; Mazvimavi and Twomlow, 2009). According to Kassam et al. (2009), of the 106 million ha reported to be under CA worldwide, Africa contributes only 0.4% with the majority of this being on commercial farms in South Africa. In smallholder agriculture in Africa, the principal factor limiting the area of cropped fields is the number of necessary weedings following planting (Kent et al., 2001).

In southern Africa there have been reports of a doubling in labor required for hand hoe weeding of maize and cotton grown under planting basins (Haggblade and Tembo, 2003) as well as increases in weeding intensity in minimum tillage compared to conventional mouldboard plough tillage (Baudron et al., 2007; Mazvimavi and Twomlow, 2009). Research done in the region indicated that minimum tillage was associated with high weed density scores (Muliokela et al., 2001) and increased weed biomass (Vogel, 1994). Giller et al. (2009) noted that in most developed countries, the benefits of CA are underpinned by a higher dependence on herbicides to enable farmers to effectively cope with increased weed emergence and growth under CA. In fact, significant adoption of CA by smallholder farmers in Brazil only occurred when herbicides such as glyphosate (*N-phosphono-methyl glycine*) became available and affordable (Bolliger et al., 2006). Gowing and Palmer (2008) reported that many of these Brazilian farmers often resort to tillage when their access to herbicides for weed control is limited. However, herbicide use in smallholder agriculture in sub-Saharan Africa is low due to the relatively high costs and limited availability. As a result, the majority of smallholder farmers use hand hoes to weed; a method that is tedious with many smallholder households investing 50–70% of their total available labor to weeding (Chikoye et al., 2007). Despite this considerable investment in labor, crop yields remain low due to a combination of late planting, delayed weed control and poor soil fertilization (Rambakudzibga et al., 2002; Ncube, 2007).

Throughout Africa, smallholder farmers have very limited farm power resources (animal and human) and this leads to serious labor bottlenecks at the beginning of the cropping season. Early in the season weeding competes with other operations like planting and livestock herding which results in weeding often being postponed to a later date (Wall, 2007; Gianessi, 2009), when the crop has already suffered significant yield loss. In addition, all other field operations such as nitrogen fertilization are also delayed, further reducing crop yield. Thus, despite the more than 20 years of research and promotion of minimum tillage systems to smallholder farmers throughout southern Africa and Zimbabwe in particular (Twomlow et al., 2006), the issue of effective weed management under these systems has most likely limited their adoption by resource-poor farmers.

Retention of crop residues as a surface mulch has been identified as an appropriate practice for reducing early season labor requirements for weeding in minimum tillage in Zambia (Gill et al., 1992) and globally (FAO, 2010). One of the pillars of CA currently promoted by FAO (http://www.fao.org/ag/ca) is a permanent soil cover of at least 30% crop residues and/or cover crops. In temperate regions, residue mulching with crop residues has been observed to reduce both weed density and biomass (Bilalis et al., 2003). Although there is limited literature on weed suppression by mulching, there is evidence from work done in southern Africa that maize residue has suppressive effects on weed mass in minimum tillage systems (Gill et al., 1992; Vogel, 1994). However, the mulch threshold for significant weed suppression is unknown (Wall, 2007; Giller et al., 2009). Research findings suggest that thick layers of mulch are required, sometimes in the range of 15–20 t ha^{-1} of mulch (Gill et al., 1992; Christoffoleti et al., 2007). However, smallholder rainfed crop production in semi-arid areas is characterized by low residue production levels (Gowing and Palmer, 2008), with cereal residue yields typically averaging less than 2 t ha^{-1}. Furthermore, in smallholder agriculture, cereal residue is used as livestock feed in preference to using it for mulching (Giller et al., 2009). Putting all these factors together, the minimum soil cover of 30% may not be feasible, especially in marginal areas.

The objective of the present study was to determine the effect of maize mulch rates and intensity of hand hoe weeding on weed, cowpea and sorghum growth. The crops were grown under mouldboard plough, ripper tine and planting basin tillage systems in the fifth and sixth years of CA experiment with a three-year maize–cowpea–sorghum rotation as the cropping system. Due to the low and erratic rainfall, crop production in semi-arid Zimbabwe is risky and it is recommended that drought-tolerant cereal and legume crops be grown. Sorghum (*Sorghum bicolor* (L.) Moench) is one such cereal crop that is grown in addition to the staple maize (*Zea mays* L.) crop to ensure food security. Cowpea (*Vigna unguiculata* (L.) Walp), a drought-tolerant legume is one of the more commonly grown legumes by smallholders either as a sole crop or intercropped with a cereal (Ncube, 2007). The three tillage systems were representative of current conventional and minimum tillage (MT) systems being practiced in Zambia and Zimbabwe.

2. Materials and methods

2.1. Location

The study was conducted in the fifth (2008/09) and sixth (2009/10) years of a CA field experiment established in 2004 at West Acre Creek of Matopos Research Station Farm, Zimbabwe (28°30.92′E, 20°23.32′S; 1344 m above sea level). The station is characterized by semi-arid climatic conditions and is considered to be representative of climatic conditions found in southwest Zimbabwe and much of Botswana, southern Mozambique and southern Zambia (Twomlow et al., 2006). The rainfall season is unimodal with distinct wet (November–March) and dry (April–October) seasons. The wet season is characterized by highly variable rainfall (250–1400 mm) with a mean long-term annual rainfall of 580 mm. The soil at the site is derived from micaceous schists and is classified as a Chromic-Leptic Cambisol (FAO, 1998) with 45% clay, 19% silt and 36% sand in the 0–0.44 m layer (Moyo, 2001). The soil is prone to waterlogging during exceptionally wet seasons. In 2008, the upper 0.15 m soil layer had a pH (water) of 6, a soil organic carbon content of 1.2% and bulk density of 1.4 g cm^{-3} (Mupangwa, 2009).

2.2. Treatments and experimental layout

In 2004, an experiment was designed to compare the effect of minimum tillage and maize residue mulching on soil water and crop yields of a three-year maize–cowpea–sorghum rotation (Mupangwa, 2009). The experiment was set up as a split-plot with plots arranged in a randomized complete block design with three replications. Tillage system was the main plot (63 m × 6 m) factor and maize residue mulching the sub-plot (8 m × 6 m) factor. In 2008 and 2009, hand hoe weeding intensity was added as a treatment factor at two levels (high and low weeding intensity). The weeding treatments were superimposed on sub-plots that received maize mulch rates of 0, 4 and 8 t ha^{-1} with each mulch rate replicated twice per main plot. Weeding at the high intensity treatment was carried out a week before planting, a week after planting (WAP), at 5 WAP and before harvesting (weeding W1 to W4 in Fig. 1). The high weeding intensity treatment followed the

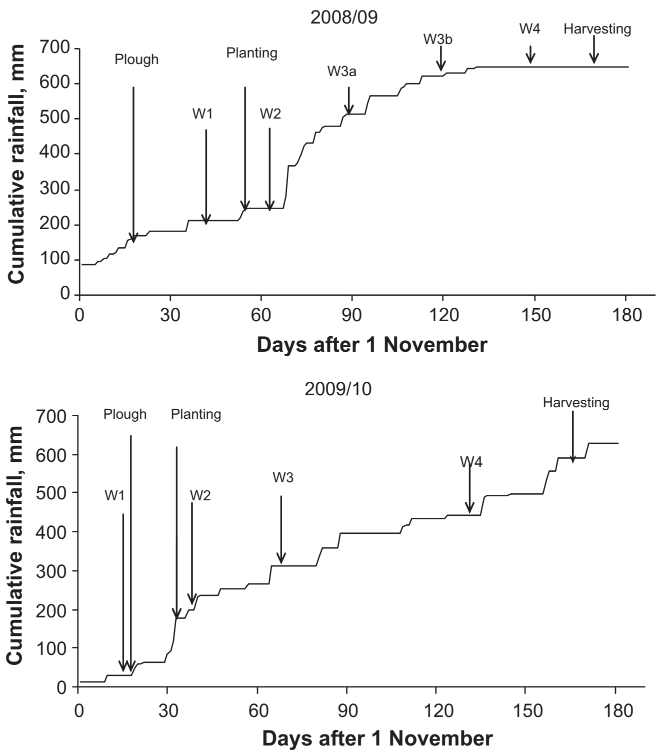

Fig. 1. Cumulative daily rainfall received and the timing of crop management practices at Matopos, Zimbabwe in the 2008/09 and 2009/10 cropping seasons. W1, W2, W3 and W4: high intensity hoe weeding operations; W1 and W3: low intensity hoe weeding operations.

CA recommendation of frequent weeding aimed at minimizing weed seed return to the soil seed bank. This weeding regime's objective was to provide a clean seedbed for the crop, remove the first weed flush to emerge with the crop, reduce weed competition during the critical first 40 days of crops' growth and remove last weed cohorts emerging at end of the rains. The low weeding intensity treatment comprised hoe weeding a week before planting and at 5 WAP (weeding W1 and W3 in Fig. 1). This treatment simulated the smallholder farmer practice of planting into a clean seedbed after spring mouldboard ploughing and then hoe weeding 40 or more days after planting (Twomlow et al., 2006).

2.3. Crop management

2.3.1. Land preparation

Weeds were removed from all plots using hand hoes in June 2008. Maize residue was uniformly applied to sub-plots as surface mulch in August 2008. Planting basin (PB) and ripper tine (RT) tillage were carried out in September 2008 as per guidelines of the Zimbabwean CA Taskforce (Twomlow et al., 2008). Planting basins with dimensions of 0.15 m (length) × 0.15 m (width) × 0.15 m (depth) were dug using hand hoes at an inter-row spacing of 0.9 m and intra-row spacing of 0.6 m. Rip lines were opened at 0.9 m inter-row spacing using a commercially available ZimPlow® ripper tine attached to the beam of a donkey-drawn mouldboard plough. A ripping depth of between 0.15 m and 0.18 m was achieved with a single pass of the implement. In November 2008, to prevent incorporation of maize residue during ploughing, residues were removed from mouldboard plough (MBP) plots before ploughing. At the first effective rains (50 mm) ploughing was done using a donkey-drawn ZimPlow® VS200 mouldboard plough and a depth of 0.15 m was achieved. Maize residues were returned to MBP plots after which planting furrows were opened using hand hoes at an inter-row spacing of 0.6 m recommended for cowpeas in Zimbabwe. No basal fertilizer was applied.

The same land preparation methods were carried out in the 2009/10 cropping season. However, two additional dry-season hoe weedings were done, in August 2009 before mulching and in September 2009 prior to PB and RT tillage, in order to keep plots weed-free. The high weed growth observed during the period between June and September 2009 was probably due to residual soil moisture from the wet 2008/09 season that may have promoted increased weed germination and growth. The basin and rip line positions were maintained across the two seasons, as they had been in the previous four seasons (Mupangwa, 2009). In the 2009/10 season, cattle kraal manure (18% organic carbon, 0.13% N, 0.11% P) was applied as a basal soil fertility amendment at a rate of 3 t ha^{-1}. Manure was spot applied into planting basins and banded along the rip line in September 2009. As in the 2008/09 season, ploughing was done at first effective rains in November 2009 and planting furrows were opened at the recommended spacing for sorghum of 0.75 m and manure was banded along the furrows.

2.3.2. Planting and management

Since the majority of smallholder farmers in Zimbabwe commonly retain seed of minor crops such as cowpea, retained cowpea seed of an early maturing, semi-determinate cowpea variety, IT 86D-719 (source: IITA, Nigeria) was planted in all tillage systems on 26 December 2008. In both PB and RT, the recommendation of the Zimbabwean CA Taskforce (Twomlow et al., 2008) was followed in planting cowpea. Five cowpea seeds were planted per planting basin and thinned to four seedlings at 4 WAP to give a cowpea density of 74,074 plants ha^{-1}. In RT tillage, two cowpea seeds were planted per planting station and stations were spaced 0.15 m apart. At 4 WAP, the cowpea seedlings were thinned to one seedling per planting station to achieve the same cowpea density in RT as in PB. In MBP, one cowpea seed was planted at an intra-row spacing of 0.25 m to achieve the recommended cowpea density of 66 667 plants ha^{-1}. The cowpea crop was not fertilized since most smallholder farmers neither apply manure nor inorganic fertilizer to legume crops (Ncube, 2007). Thiodan 35EC (80 ml in 20 l water) was sprayed on cowpea at 4 WAP and during flowering to control aphids (*Aphis craccivora* L.). Thinning, spraying and weeding were carried at the same time in all tillage systems. The cowpea crop was harvested in April 2009.

An early maturing sorghum variety Macia was planted on 2 December 2009. In PB, the same planting and thinning method used in cowpeas was used to give a sorghum density of 74,074 plants ha^{-1}. In both RT and MBP, sorghum seed was dribbled along planting furrows and thinned at 4 WAP to an intra-row spacing of 0.15 m to give a density of 74,074 plants ha^{-1} in RT and 88 889 plants ha^{-1} in MBP. Ammonium nitrate (34.5% N) was applied to sorghum at a rate of 20 kg N ha^{-1} as topdressing at 5 WAP. Planting, weeding and fertilizer application were carried at the same time in all treatments. Sorghum was harvested in April 2010.

2.4. Data collection

2.4.1. Weed biomass and density

Weed density and biomass per sub-plot were determined from two randomly placed 0.5 m^2 quadrats. Weed density data was collected before weeding at 1 week before planting, 1 and 4 WAP; and every four weeks thereafter. Weed biomass in the 2008/09 season was collected starting at 4 WAP, and at all weed sampling times in 2009/10 season. Weeds sampled in each sub-plot were cut at ground level and oven-dried at 60 °C to constant weight and the dry weight determined.

2.4.2. Crop yield

The number of plants, grain yield and stover (above-ground biomass minus grain) dry matter were determined from a net plot of four central rows each 6 m long in both cowpea and sorghum. In addition, cowpea pod number per plant and sorghum heads per net plot were measured. Grain yield was standardized to 12.5% moisture content.

2.5. Statistical analysis

Prior to analysis, weed density and biomass data were square root transformed ($x + 0.5$) to homogenize variances (Gomez and Gomez, 1984). All weed and crop data were subjected to analysis of variance using GenStat Release 9.1 (Lawes Agricultural Trust, 2006). The means of the treatments were separated by least significant difference (LSD) at 5% level of significance.

3. Results and discussion

3.1. Seasonal rainfall

In both seasons, the start of the rainy season and distribution of rain within the season influenced the timing of crop management practices (Fig. 1). The low precipitation received after ploughing in the 2008/09 cropping season resulted in cowpea being planted in the last week of December 2008, more than a month after ploughing. The month of January 2009 received 42% of the total 2008/09 seasonal rainfall and the incessant rains led to re-weeding of all sub-plots (weeding W3a and W3b in Fig. 1) as hoe weeding was observed to be ineffective under the excessively wet soil conditions. The continuous rainfall also made it difficult to spray Thiodan 35EC for aphid control at two week intervals as is recommended. Cowpea establishment was poor in this season probably due to high seedling mortality as cowpea is prone to fungal diseases under wet conditions. The 2009/10 season was characterized by good early rainfall distribution and consequently sorghum was planted in early December 2009, a week after ploughing. The rains peaked in December (29% of total seasonal rainfall) but declined from January to March 2010. However, the rains increased in April 2010 resulting in 20% of the season's rains falling after the sorghum crop had reached physiological maturity. Both seasons received more than the long-term mean annual rainfall (580 mm per annum) for Matopos Research Station.

3.2. Weed density and biomass

3.2.1. Effects of tillage

Tillage had a significant ($P < 0.05$) effect on weed density one week before cowpea was planted where ripper tine had 3-fold and PB 2-fold the weed density (3.4 m^{-2}) of the MBP system. Weed emergence under MT systems was higher than under MBP because without soil inversion weed seeds remained in the soil surface layer where suitable environmental conditions stimulated weed germination. The surface soil layer is characterized by high light penetration, high levels of O_2 gas, thermal fluctuations and moisture oscillations which often trigger seed germination (Benvenuti et al., 2001). In contrast, under MBP most weed seeds were buried at soil depths where conditions induced seed dormancy leading to low weed emergence. Similar results were obtained by Kombiok and Alhassan (2007) in Ghana and Mashingaidze et al. (2009) in Zimbabwe which demonstrated that a heavier and earlier weeding burden resulted in MT than in conventional MBP systems. This may necessitate earlier weeding in RT and PB tillage systems than would be the case in MBP, at a time when labor demand is still high. The low weed infestation observed in MBP plots at 28 days after ploughing in this study

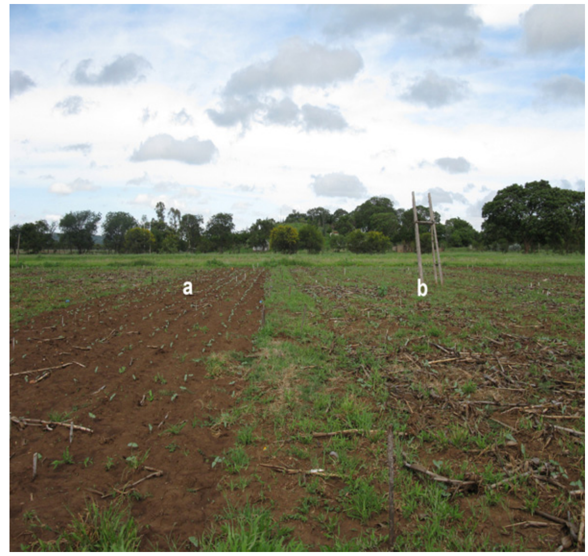

Plate 1. Low weed infestation in (a) MBP compared to (b) RT a week after cowpea was planted at Matopos Research Station during the 2008/09 season. *Abbreviations:* MBP – mouldboard plough and RT – ripper tines.

(Plate 1) is in agreement with the findings of Mabasa et al. (1998) from on-farm studies in Zimbabwe that showed that spring ploughing reduced the need for subsequent weeding for up to four weeks.

In cowpeas, MT systems were found to have significantly ($P < 0.05$) greater weed biomass than MBP at 4 WAP (Table 1). However, this effect was confounded within the significant ($P < 0.05$) tillage × weeding intensity interaction which showed that MT systems had 37% more weed biomass than MBP only in the low weeding intensity treatment (Fig. 2). The absence of a significant difference between MT and MBP systems when a second within cropping season weeding was carried out a week after cowpea was planted demonstrated the need for more frequent hoe weeding in MT systems to achieve weed levels comparable to those in MBP. The same trend of higher weed growth in the less intensive tillage systems was also observed in sorghum. A week before sorghum was planted; PB had the highest

Table 1
Tillage, maize mulch rate and hand hoe weeding intensity effect on weed biomass in cowpea grown at Matopos, Zimbabwe in 2008/09 season.

Treatment	Weed biomass (kg ha^{-1})			
	4 WAP	9 WAP	13 WAP	Total[a]
Tillage				
MBP	29.4	17.5	21.6	41.9
RT	42.8	14.2	19.0	49.6
PB	40.5	14.6	18.4	48.1
P-value	<0.05	>0.05	>0.05	>0.05
LSD	8.26			
Mulch (t ha^{-1})				
0	36.8	15.5	18.2	44.8
4	41.6	15.2	20.7	50.4
8	34.4	15.5	20.0	44.4
P-value	>0.05	>0.05	>0.05	>0.05
Weeding intensity				
Low	51.9	15.9	25.1	61.6
High	23.2	14.9	14.2	32.6
P-value	<0.001	>0.05	<0.001	<0.001
LSD	6.49		3.587	5.48

Square root ($x + 0.5$) transformed data presented; LSD, least significant differences of means (5% level).
Abbreviations: MBP – mouldboard plough; RT – ripper tine; PB – planting basin.
[a] Cumulative weed biomass for 4, 9 and 13 weeks after planting (WAP).

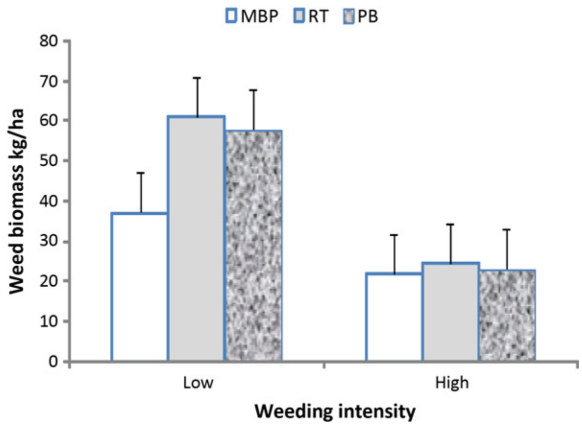

Fig. 2. Tillage × weeding intensity interaction on weed biomass at 4 WAP in cowpea grown in 2008/09 at Matopos, Zimbabwe. Bars represent LSD. *Abbreviations:* MBP – mouldboard plough; RT – ripper tine; PB – planting basins.

weed biomass ($P < 0.05$) of the three tillage systems (Table 2). The weed biomass in PB was 58% more than in MBP with weed biomass in RT being intermediate but not significantly different to that in MBP. In the week after sorghum was planted, MT systems had double ($P < 0.05$) the weed biomass of MBP. As a result, total weed biomass of MT systems was 16% higher ($P < 0.01$) than that of MBP (Table 2). Since weed density measured after planting did not significantly vary with tillage in both seasons, the differences observed in weed biomass must have been mainly due to variation in weed growth between tillage systems.

Weeds such as *Commelina bengahalensis* L., *Alternanthera repen* (L.) Link., *Boerhavia diffusa* L., *Leucas martinicensis* (Jacq.)R.Br. and some grass species were observed to grow rapidly with the first effective rains in MT systems in both seasons. These weeds had deep root systems and/or a perennial growth habit that enabled them to tolerate the long dry season. The undisturbed root systems and rhizomes under MT systems may have given these weeds a head start at the onset of the rainy season and resulted in greater weed biomass accumulation under MT systems than MBP. Perennial weeds have been reported to establish rapidly in non-inversion tillage fields in studies done by Makanganise et al. (2001) in Zimbabwe and Kombiok and Alhassan (2007) in Ghana. In addition, the weeds *C. bengahalensis* and *A. repens* as well as *Portulaca oleracea* L., were observed to quickly regenerate after hoe weeding under wet conditions. This suggests that shallow hoe weeding as done in this study was not fully effective in controlling these weeds. It may, in fact, have increased weed infestations when the cut stems gave rise to new weed plants.

Both PB and RT tillage systems had greater weed growth than MBP early in the cropping season. This period falls within the first third of most crops life cycle that is required to be kept weed free to avert yield loss (Mashingaidze, 2004). According to Akobundu (1987) sorghum required 35 and cowpea 40 weed free-days after planting to prevent weeds from causing significant yield reduction. The increased weed growth under MT in both the 5th and 6th years of the CA experiment contradicts literature (Wall, 2007; FAO, 2010) that states that weed growth will increase in the first years but decline and become easier to control with time in CA. The high early season weed growth suggests a potential for increased weed competition that would probably necessitate early weed control strategies to be implemented if significant crop yield losses are to be averted.

3.2.2. Effects of mulch rate

Maize residue mulching significantly ($P < 0.01$) increased total weed density in cowpea by at least 7% compared to the un-mulched treatment (Table 3). Although the trend of increased weed density with mulching was observed at all sampling times in cowpeas, the effect was only significant as from the middle of the 2008/09 cropping season. Weed density increased by at least 16% ($P < 0.05$) at 9 WAP and 20% ($P < 0.01$) at 13 WAP in mulched plots. In sorghum, the maize mulch rate of 4 t ha^{-1} had the highest weed density at 4 WAP and when summed across all sampling times (Table 3). Maize mulch application was also associated with high weed biomass in sorghum at both 9 and 13 WAP (Table 2). Weed biomass increased by at least 22% ($P < 0.01$) at 9 WAP and 13% ($P < 0.05$) at 13 WAP under mulching. Consequently, it would

Table 2
Tillage, maize mulch rate and hand hoe weeding intensity effect on weed biomass in sorghum crop grown in 2009/10 season at Matopos, Zimbabwe.

Treatment	Weed biomass (kg ha^{-1})					
	−1[a] WAP	1 WAP	4 WAP	9 WAP	13 WAP	Total[b]
Tillage						
MBP	8.9	1.8	20.0	13.6	5.0	29.9
RT	10.2	5.8	22.3	14.5	6.0	34.8
PB	14.4	7.3	26.0	14.7	7.1	40.3
P-value	<0.05	<0.05	>0.05	>0.05	>0.05	<0.01
LSD	3.49	2.62				4.13
Mulch (t ha^{-1})						
0	12.3	5.6	24.9	11.5	16.4	34.2
4	11.4	4.2	21.8	14.2	21.3	35.3
8	9.7	5.0	21.6	17.1	18.6	35.7
P-value	>0.05	>0.05	>0.05	<0.01	<0.05	>0.05
LSD				2.63	1.16	
Weeding intensity						
Low	10.6	5.2	31.6	16.8	9.0	47.7
High	11.6	4.6	14.0	11.8	3.0	22.3
P-value	>0.05	>0.05	<0.001	<0.001	<0.001	<0.001
LSD			4.16	0.70	6.89	5.03

Square root ($x + 0.5$) transformed data presented; LSD, least significant differences of means (5% level).
Abbreviations: MBP – mouldboard plough; RT – ripper tine; PB – planting basins.
[a] 1 Week before planting.
[b] Cumulative weed biomass of 1–13 weeks after planting (WAP).

Table 3
Maize mulch rate and hand hoe weeding intensity effect on weed density in cowpea and sorghum crops at Matopos, Zimbabwe.

Crop	Treatment	Weed density (m^{-2})				
		1 WAP	4 WAP	9 WAP	13 WAP	Total[a]
Cowpea	Mulch (t ha^{-1})					
	0	5.8	7.6	5.8	5.9	13.0
	4	7.2	8.4	6.9	7.1	14.6
	8	5.6	8.2	6.7	7.1	13.9
	P-value	>0.05	>0.05	<0.05	<0.01	<0.01
	LSD			0.85	0.60	1.87
	Weeding intensity					
	Low		8.1	6.5	7.1	14.2
	High		8.1	6.5	6.3	13.5
	P-value		>0.05	>0.05	<0.05	>0.05
	LSD				0.79	
Sorghum	Mulch (t ha^{-1})					
	0	8.0	10.8	5.5	5.2	15.7
	4	7.6	12.6	5.8	5.5	17.0
	8	6.5	10.7	6.3	5.0	15.0
	P-value	<0.05	<0.05	>0.05	>0.05	<0.05
	LSD	1.07	1.30			1.44
	Weeding intensity					
	Low	8.2	14.5	6.9	6.5	19.4
	High	6.7	8.2	4.7	3.9	12.4
	P-value	<0.01	<0.001	<0.001	<0.001	<0.001
	LSD	0.94	1.14	0.75	1.00	1.23

Square root ($x + 0.5$) transformed data presented; LSD, least significant differences of means (5% level).
[a] Cumulative weed density of 1–13 weeks after planting (WAP).

appear from our observations that the retention of maize residue rather than suppressing weeds as is widely reported (Bilalis et al., 2003; FAO, 2010) increased the emergence of weed seedlings and their subsequent survival rate compared to un-mulched plots.

Soils under maize mulch were reported to have had higher soil water content than un-mulched soils by Mupangwa et al. (2007) in the study that preceded the one we are reporting. It may, therefore, be that the high weed growth under mulch was due to improved water conservation than in un-mulched soils. Corresponding results were obtained by Buhler et al. (1996) in the USA who reported that in a below average rainfall season the retention of 5 t ha^{-1} of maize residue resulted in increased weed density of some annual weed species due to improved soil moisture conditions. According to Mohler and Teasdale (1993) "safe sites" maybe created under the residue where more uniform soil moisture and moderate temperatures are maintained during hot dry periods and these can increase weed germination and growth. While an increase in weed density and biomass at the end of the crop's life cycle may not be important in terms of crop/weed competition, these late weeds if allowed to shed seeds add to the weed seed bank and become a source of future weed infestations. In fact weeds growing over the winter period in Zimbabwe have been shown to deplete residual soil moisture (Bruneau and Twomlow, 1999). In order to prevent replenishment of the soil weed seed bank and conserve residual soil moisture for the next season, smallholder farmers should be encouraged to control the late season weeds.

Maize residue mulching did, however, suppress weed growth but this was only observed in sorghum and confined to early cropping season. Retention of maize mulch decreased weed density ($P < 0.05$) by 19% at 1 WAP (Table 3) and weed biomass ($P < 0.01$) at 4 WAP in PB only (Fig. 3). In this study, maize residue mulching was observed to provide a soil cover of 60% at 4 t ha^{-1} and 100% at 8 t ha^{-1} and the shading effect of the mulch probably led to a reduction in soil temperature oscillations and the amount of light reaching the soil surface. Since temperature and light are important cues for seed dormancy and germination for most annual weed species, shading of the soil surface by the mulch early in the season before the sorghum canopy had fully formed resulted in suppression of weed emergence and growth. Bilalis et al. (2003) observed that both weed density and biomass decreased with increased wheat residue mulch on an organic farm in Greece. In Zambia, Gill et al. (1992) found that 5 t ha^{-1} of grass (*Cynodon* species) residues significantly reduced weed biomass in the first 42 days of maize growth in a MT system. Mashingaidze et al. (1995) in work done in Zimbabwe using wheat residues as mulch also observed greater suppression in weed emergence in MT systems than in conventional tillage. The concentration of weed seeds in the soil surface in MT systems may make them more susceptible to the effects of mulch on weed germination than weed seeds in MBP that are buried at greater soil depths.

While the observed weed suppression may be useful in reducing labor demands early in the cropping season, only a minority of smallholder farmers are able to retain maize residue at the levels (4 t ha^{-1} or more) used in this study in their fields. The amount of crop residue available for use as mulch is limited by low biomass production under rainfed conditions in semi-arid areas of southern Africa (Wall, 2007). In addition, the multiple uses of crop residues that include residue use as feed for livestock in the mixed crop/livestock farming systems common under smallholder agriculture in southern Africa further reduce crop residue availability for mulching. Due to these constraints, the rates of crop residue available for mulching in marginal areas are so low that they are unlikely to eliminate the need for early weeding in MT systems as suggested by Gill et al. (1992).

3.2.3. Effect of intensity of hoe weeding

In cowpea, the low weeding intensity treatment increased ($P < 0.05$) weed density by 13% at 13 WAP (Table 3) and this translated into significantly ($P < 0.001$) higher weed biomass measured at 13 WAP (Table 1). At 4 WAP, higher weed biomass was observed in the low weeding intensity treatment than in high weeding intensity only in PB and RT tillage systems (Fig. 2). There was no difference in weed biomass at 4 WAP between the MT and MBP tillage systems at the high weeding intensity treatment. Similar results were obtained by Torresen et al. (2003) in a field study in Norway where the use of herbicides diminished differences between tillage systems compared to where no herbicides were applied. The high weeding intensity treatment significantly ($P < 0.001$) reduced total weed biomass (between 4 and 13 WAP) by 48% compared to the low weeding intensity treatment in cowpeas. In sorghum, weeding four times within the cropping season significantly reduced weed biomass and density at 4, 9 and 13 WAP (Tables 2 and 3). In addition, the plots that had received the high weeding intensity treatment when cowpea was grown in 2008/09 season had a weed density at 1 WAP that was 19% ($P < 0.01$) less than that of the low weeding intensity

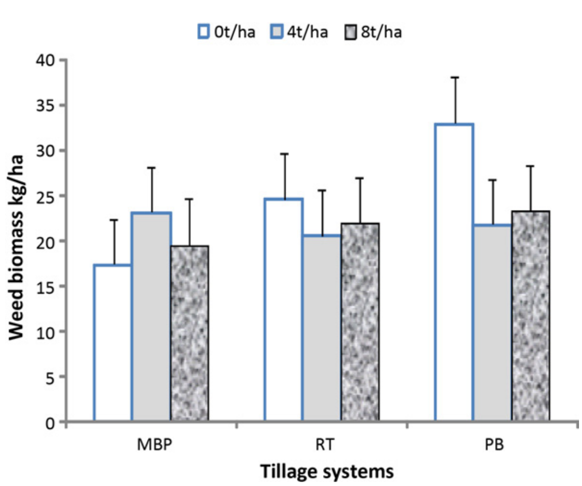

Fig. 3. Tillage × maize mulch rate interaction on weed biomass at 4 WAP in sorghum at Matopos, Zimbabwe in the 2009/10 season. Bars represent LSD. *Abbreviations:* MBP – mouldboard plough; RT – ripper tine; PB – planting basins.

Plate 2. Higher weed growth observed four weeks after sorghum was planted in PB sub-plot (a) weeded only before planting compared to another PB sub-plot (b) weeded at one week before planting and 1 week after planting at Matopos Research Station during the 2009/10 season. *Abbreviations:* PB – planting basins.

treatment (Table 3). When summed over all weed sampling times after sorghum was planted, the high weeding treatment reduced weed density by 36% and weed biomass by 53% compared to the low weeding intensity treatment.

Thus, frequent hand hoe weeding, as demonstrated in a number of studies throughout Africa (Mashingaidze, 2004; Chikoye et al., 2007; Gianessi, 2009), can significantly reduce both weed emergence and growth across the cropping season. It was also effective in reducing early season weed growth in sorghum grown under MT (Plate 2) to the level found in MBP. However, the four hoe weedings in addition to the dry season weeding(s) carried out in this study may not be a feasible option for the majority of resource-poor smallholder farmers. Although promoters of CA argue that weed management inputs decline after the first years (Wall, 2007; FAO, 2010) the findings from this study after four years of CA appear not to support this. Bolliger et al. (2006) report that the majority of smallholder zero-till (CA) farmers in southern Brazil find it difficult to control weeds without herbicides more than 20 years after replacing ploughing with zero-till. This dependence by zero-till smallholder farmers in Brazil on herbicides for effective weed control is reported to have increased herbicide use by 17% compared to conventional tillage.

Consequently, this high weeding demand for MT systems will probably limit the area under these tillage systems in smallholder crop production systems. The requirement for frequent weeding throughout the cropping season is likely to exacerbate the labor constraints faced by the majority of smallholder farmers in southern Africa. It is, therefore, likely that the area under PB and RT systems will be limited by the difficulty experienced by smallholder farmers in carrying out timely and frequent year-long weed management over large areas using the labor-intensive hand hoe weeding method.

3.3. Crop performance

Cowpea population in the 2008/09 season was less than 50% of the recommended population of 66 667 plants ha^{-1}. The use of retained seed, late planting and the incessant rainfall received in January 2009 (Fig. 1) likely contributed to poor crop establishment. Conventional MBP had the highest cowpea density and number of pods per plant which translated into significantly ($P < 0.05$) higher grain yield (81%) than in MT systems (Table 4). Cowpea grain yield in 2008/09 season was low and close to the Zimbabwe national average yield for smallholder farmers of 300 kg ha^{-1} (Nhamo et al., 2003). However, high grain yield of over 1200 kg ha^{-1} of the cowpea cultivar IT86 D-179 have been reported by Mupangwa (2009) in the first phase of the maize-cowpea-sorghum rotation of this CA experiment and by Fatokun (2002) in Nigeria. In both studies, there was good cowpea establishment and growth due to conducive environmental and management conditions. Olufajo and Singh (2002) identified low plant population as one of the major factors limiting yield in cowpea production. In addition, there was probably poor aphid control in our study as the incessant rains during January 2009 (Fig. 1) limited the number of spray applications to only two during the period with severe aphid infestation. Schulz et al. (2001) reported that cowpea that is not adequately protected from insect damage produces less grain and more leaf and vine dry matter. This is borne out by the high cowpea stover (>1300 kg ha^{-1}) in all the tillage systems (Table 4) and this translated to low harvest indexes of between 8 and 17%. Maize residue mulching had no effect on cowpea yield (Table 4) in this relatively wet season. Although the high weeding intensity treatment increased cowpea grain yield by 23%, the yield difference between the two weeding intensities was not statistically significant. Akobundu (1982) found at least two weedings in the first 5 weeks of cowpea growth to be sufficient to avert yield decline from weed infestation. Hoe weeding in the low weeding intensity treatment was carried out within this critical period. It may, therefore, be difficult to convince smallholder farmers to carry out more weedings later in the season for no additional yield benefit especially for a crop that it is neither a staple nor cash crop.

In sorghum, conventional MBP had the highest density at harvesting, with the density in PB being 81% lower than in MBP (Table 5). The wide inter-row spacing of 0.9 m that is recommended in PB and RT tillage systems by the Zimbabwe CA Taskforce (Twomlow et al., 2008) may have been one of the factors responsible for the low sorghum density in MT systems. The low sorghum stand in MT systems probably contributed to the low grain yield as sorghum grain yield at Matopos in 2009/10 season was positively correlated ($P < 0.01$; $r^2 = 0.411$) with sorghum density. The sorghum grain yield obtained under MBP was 497 kg greater than yield under the RT and 1557 kg more than for PB with the same trend in sorghum stover yield. Maize residue mulching significantly ($P < 0.05$) reduced sorghum grain yield by 15% (Table 5). The high weed biomass under mulched plots at both 9 and 13 WAP (Table 2) probably reduced sorghum yield through increased competition during the boot stage. On average, the sorghum crop

Table 4
Response of cowpea yield to tillage, maize mulch rate and hand hoe weeding intensity at Matopos, Zimbabwe in 2008/09 season.

Treatment	Density (plants ha^{-1})	Pods (plant^{-1})	Grain (kg ha^{-1})	Stover (kg ha^{-1})
Tillage				
MBP	33,385	23	413	4588
RT	17,593	21	272	1327
PB	26,646	14.6	228	1392
P-value	<0.05	<0.01	<0.05	>0.05
LSD	11,615	4.2	120.2	
Mulch (t ha^{-1})				
0	21,811	21	351	3685
4	25,874	19	304	1776
8	29,938	19	258	1847
P-value	>0.05	>0.05	>0.05	>0.05
Weeding intensity				
Low	26,406	18	273	2921
High	25,343	21	335	1951
P-value	>0.05	<0.05	>0.05	>0.05
LSD		2.4		

LSD, least significant differences of means (5% level).
Abbreviations: MBP – mouldboard plough; RT – ripper tine; PB – planting basins.

Table 5
Sorghum yield response to tillage, maize mulch rate and hand hoe weeding intensity at Matopos, Zimbabwe in 2009/10 season.

Treatment	Density (plants ha^{-1})	Heads (ha^{-1})	Grain (kg ha^{-1})	Stover (kg ha^{-1})
Tillage				
MBP	71,698	71,327	4159	4801
RT	59,902	56,790	3662	3180
PB	30,780	36,446	2602	2168
P-value	<0.05	<0.05	<0.05	<0.01
LSD	17,438.9	18,848.7	752.4	925.4
Mulch (t ha^{-1})				
0	58,961	55,062	3871	3072
4	58,477	57,181	3282	3525
8	53,951	52,320	3271	3552
P-value	>0.05	>0.05	<0.05	>0.05
LSD			485.9	
Weeding intensity				
Low	58,745	56,958	3113	2937
High	55,511	52,750	3836	3829
P-value	>0.05	>0.05	<0.05	<0.001
LSD			526.7	339.5

LSD, least significant differences of means (5% level).
Abbreviations: MBP – mouldboard plough; RT – ripper tine; PB – planting basins.

in this study was observed to have reached 50% booting at 9 WAP. Since potential seed number per panicle is determined during the boot stage (Vanderlip, 1993) increased weed competition may have reduced seed number per panicle and ultimately grain yield. This is because seed number per panicle is highly related to sorghum grain yield (Heinrich et al., 1983). Weed biomass at 13 WAP was observed to be negatively correlated ($P < 0.01$; $r^2 = 0.36$) to sorghum grain yield with the same trend observed at 9 WAP. The grain yield obtained under the low weeding intensity treatment was significantly ($P < 0.05$) lower (19%) than that obtained at the high weeding intensity treatment (Table 5) indicating the benefits of high weeding intensity on sorghum yield.

4. Conclusion

Even after more than four years of CA, MT systems were found to have higher early season weed growth than MBP in both cowpea and sorghum. This would require early and more frequent weeding that is likely to exacerbate existing labor bottlenecks in smallholder crop production systems. There was generally limited benefit obtained from retaining maize residue as surface mulch as it was mostly associated with high weed growth and low grain yield in both crop species. Overall weed growth was decreased and crop grain yield improved with increasing hand hoe weeding intensity irrespective of the tillage systems. However, most smallholder farmers lack sufficient labor to carry out the four hoe weedings as done in this study. Low grain yields were realized in MT systems probably due to poorer crop establishment compared to MBP. In order for CA to be practiced on a large area by smallholder farmers, there is need for research on the economical feasibility of using herbicides for early season weed control.

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